STEPS	CONSIDERATIONS
Consult with Government Agencies	• Coordinate with government agencies initially to set site-specific treatment goals and during the treatment and monitoring process. • All site characterization/assessment plans, sampling plans, and monitoring plans must be approved by the Alaska Department of Environmental Conservation (ADEC).
Characterize Site	• What spilled? • What is the tundra type? • What are the effects of the spill residuals on the soils, hydrology, vegetation? • Do wildlife or humans use the site?
Set Treatment Goals	**General Tundra Treatment Goals** • Reduce the toxicity, mobility and volume of spill residuals to (a) allow revegetation, (b) control risks to wildlife, aquatic and human receptors, and (c) return affected tundra to original state with similar plant species composition and abundance and to restore original value to wildlife and humans. • Protect sensitive tundra soils from physical damage and induced thermal effects
Select Treatment Tactics	**To The Extent Practicable, Select Tactics To:** • Avoid or minimize treatment impact. • Achieve a balance between (a) the impact of abandoning the spill residuals on site and (b) physical impacts of treatment and (c) length of recovery time.
Assemble Tactics into a Strategy	• A variety of tactics may be needed throughout the treatment process, or different tactics many be needed at different locations. • The same tactics may have to be applied more than once.
Monitor Treatment and Recovery	• Coordinate with government agencies to select or create acceptable monitoring methods and to determine when treatment goals have been reached.

STEP 1: GOVERNMENT AGENCY CONSULTATION

Coordinate with appropriate agencies before initiating a treatment program. All site characterization/assessment plans, analytical sampling plans, and monitoring plans must be approved by the Alaska Department of Environmental Conservation (ADEC). Always work with agencies to set site-specific short- and long-term goals.

STEP 2: CHARACTERIZE SITE

In order to set treatment goals and identify an appropriate treatment strategy, gather information about the site. Consider the tundra type (Tactic P-2) and important site and spill characteristics. Determine risk to humans and wildlife according to agency requirements.

Tundra Type

The nature and severity of spill impact vary with the tundra type. The high water content of wet tundra soils provides some protection to the root mat from crude oil and fuel spills, which tend to float on the water. Dry tundra soils are highly susceptible to oil-based substances that are absorbed by the dry and porous root mat, displacing the air and making the soil unable to transport water to plant roots. The dry mineral soils in the active layer have the potential to absorb crude oil, fuels, and water-soluble substances. In moist or wet tundra, water can slow the movement of non-water-soluble substances into the soil pore spaces and root mat. In these cases, oiled foliage may be killed, but the roots may survive and grow the following spring.

The sensitivity of different tundra types to the physical impacts of response and treatment tactics differs also. Generally, wet tundra is relatively sensitive to physical damage compared to moist tundra and dry tundra, but recovers more quickly. Dry and moist tundras are less susceptible to physical disturbance but recover more slowly than wet tundra because of the dry conditions, a thin root mat, and very little organic-soil development. The dwarf shrub and lichen communities that occupy dry tundra sites are very slow to recolonize and difficult or impossible to re-establish by seed or transplant techniques. Dry tundra is found in abundance on exposed hilltops and ridges that are subject to extreme wind erosion; such sites present special problems to revegetation. All tundra types are more sensitive to physical and chemical damage when thawed.

Site Layout

The usefulness and practicability of different treatment tactics will depend on the site layout. The availability of road access to the spill site and the limitations to access created by elevated pipelines and other facilities must be considered. A simple map of the site layout should be prepared for planning a treatment strategy (Tactic AM-1). Determine how the natural topographic features and the locations of roads and other facilities can help minimize additional disturbance to the tundra. Identify the routes for mobilizing equipment and materials to the site and areas for waste accumulation. Consider maintenance operations such as snow removal from gravel pads and roads and how these could affect treatment of the site, keeping in mind that treatment may continue for several years.

Site Drainage

Treatment tactics on wet tundra sites must focus on the potential for mobilizing spill residuals into the water and subsequent offsite migration routes. Consider how water would move across the site. Sloped terrain presents a challenge to preventing the downward migration of contamination. Where natural drainage patterns transect the site, temporary diversion of water flow may be required to implement treatment tactics. It is also necessary to plan for future water events, such as spring snowmelt or the rare summer rain shower.

Spill Characteristics

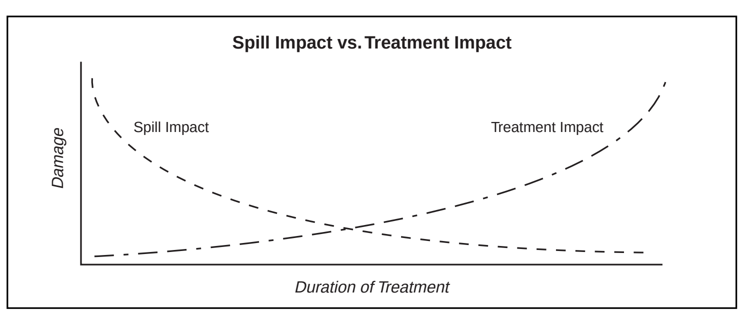
Gain a general understanding of how the spilled substance may affect that environment (Tactic P-3). Use field indicators (Tactic AM-2) to assess the apparent damage caused by the spilled substance. If appropriate, use revegetation test plots (Tactic AM-5) to determine to the extent soil treatments that may be needed. Agencies may also require sampling and laboratory analyses of the soil and water to assess baseline conditions before treatment (Tactic AM-3).

STEP 3: SET TREATMENT GOALS

Using information gained during site characterization, work with the responsible government agencies (including ADEC) to establish site-specific treatment goals before implementing treatment tactics. The general tundra-treatment goals of avoiding and/or minimizing treatment impact and balancing benefits of treatment with physical impact to site should be a guide to setting site-specific goals. Treatment goals may include a combination of reducing the toxicity, volume, and mobility of spill residuals; revegetating the site to agency-acceptable levels within a reasonable time-frame; and preventing thermal effects on tundra soils.

For the following reasons, tundra treatment goals are not always based on a single numerical value of chemical concentration in the soil:

1. ***Tundra is fragile.*** Treatments aimed at achieving state-required chemical concentrations in soils could result in enough physical damage to delay recovery of tundra vegetation or make it impossible. This concept is illustrated in the figure below. Some sites are more fragile than others.
2. ***Different tundra plants have varying tolerance to spill residuals in the soil.*** Low residual levels may adversely affect some species, while others may tolerate higher residual levels. Some sites may be characterized by an abundance of species susceptible to spill residuals, while other sites may be characterized by more spill-tolerant species.
3. ***Soil properties at a site may influence the toxicity of spill residuals to tundra plant species present.*** For example, organic soils may adsorb some of the spilled material, making it less available to plants. For this reason, a particular chemical concentration could be much more toxic to plants in mineral versus organic soils.
4. ***Government agency treatment goals may vary according to the size of the spill and the importance of the site to wildlife and humans.*** Agency goals may also vary from creating an alternate habitat that will support any type of vegetation to restoring the site to original levels of plant species abundance and diversity and ecological function.

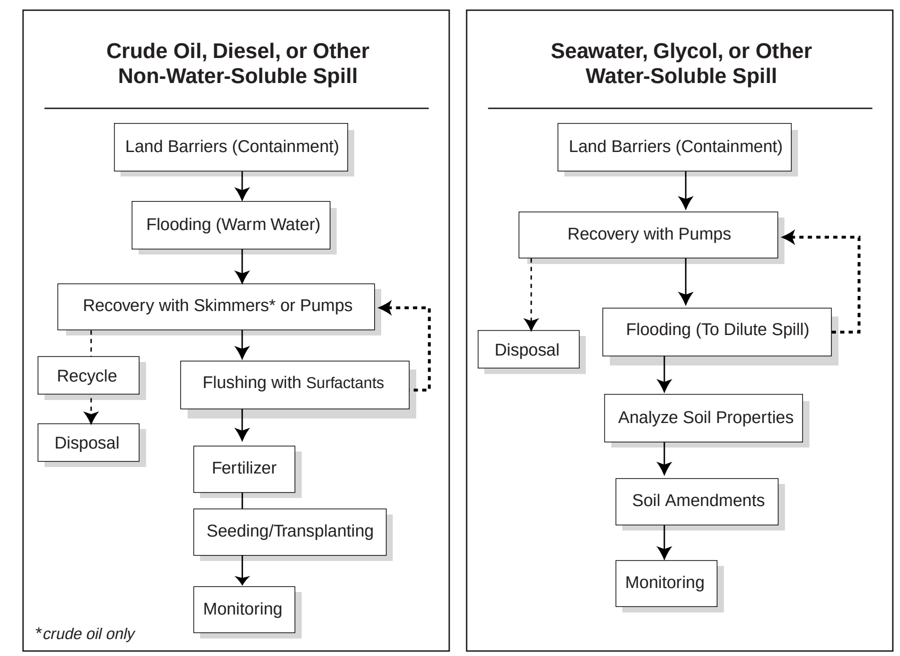


STEP 4: SELECT TREATMENT TACTICS

The treatment tactics in this manual (Tactics T-1 through T-24) describe the applicability of specific tactics, as well as special considerations and limitations. Select tactics to attain the treatment goals while at the same time avoiding excessive damage and induced thermal effects. Some tactics require mobilization of equipment and/or personnel onto the affected tundra surface, which will cause some level of physical damage and the potential for thermokarst. In cases where aggressive tactics are appropriate because of site-specific conditions or goals, design implementation plans to minimize the impact.

STEP 5: ASSEMBLE TACTICS INTO A STRATEGY

A strategy for tundra treatment is basically a group of tactics implemented sequentially. In some cases, certain tactics may be repeated in a cyclic manner until treatment goals have been attained. Review the treatment strategy regularly: Are the treatment goals feasible? Can revegetation occur at the desired rate under present site conditions? Will continued treatment cause more damage than benefit? The example treatment strategies presented in the figures that follow apply to wet, moist, or dry tundra with some seasonal limitations (see individual tactic pages). These example strategies are theoretical; individual site-specific strategies must be developed for each spill to achieve agency-required treatment goals. In general, more stringent treatment goals (e.g., high reduction of spill residuals and revegetation in the short term [2 to 5 years]) will require more aggressive treatment strategies. If a longer time frame for reduction of spill residuals and revegetation is acceptable (i.e., up to 25 years), treatment strategies can be much less aggressive. In some cases, responsible agencies and landowners may determine that "no action" or natural revegetation is the most appropriate strategy.



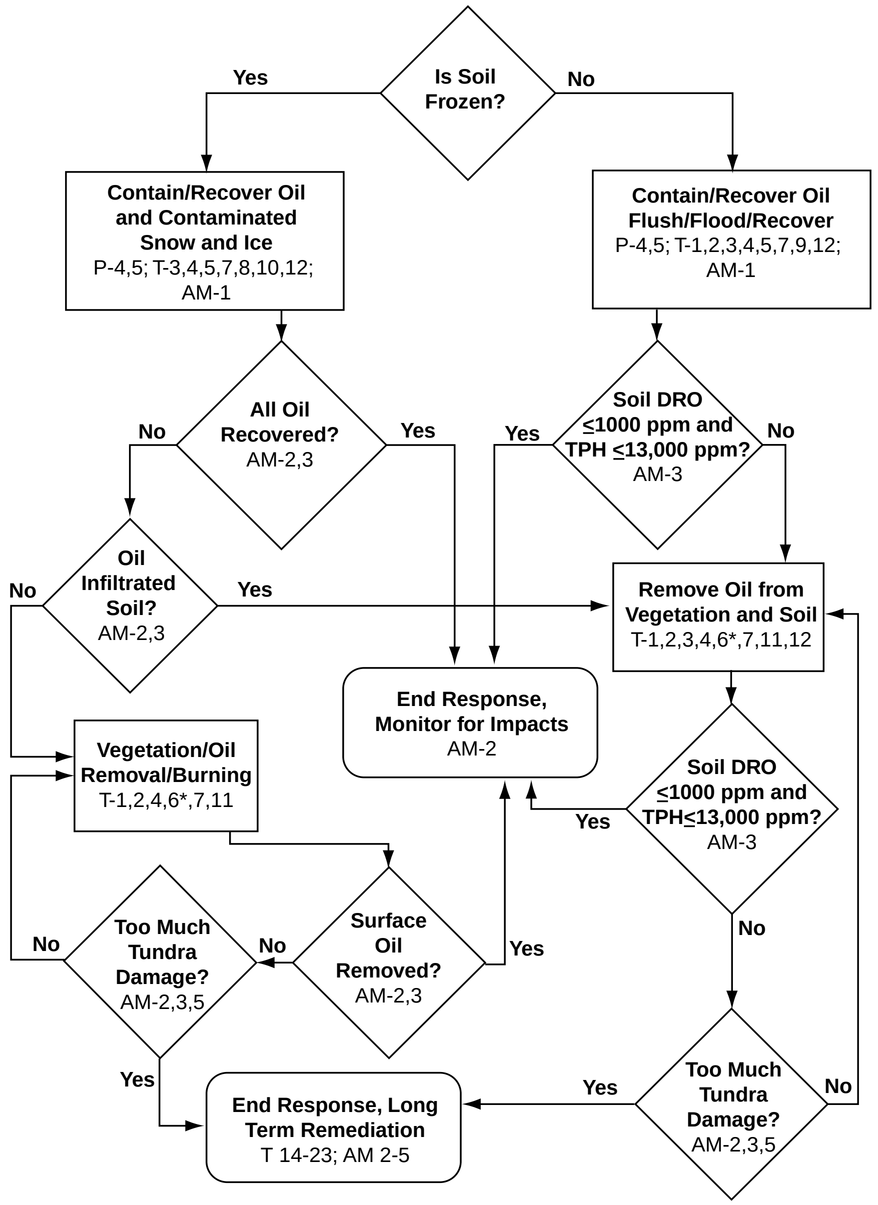
STEP 6: MONITOR TREATMENT AND RECOVERY

Coordinate with responsible government agencies (including ADEC) to prepare a monitoring program to gauge progress and determine when treatment and recovery goals have been reached. Following are possible elements of a monitoring program:

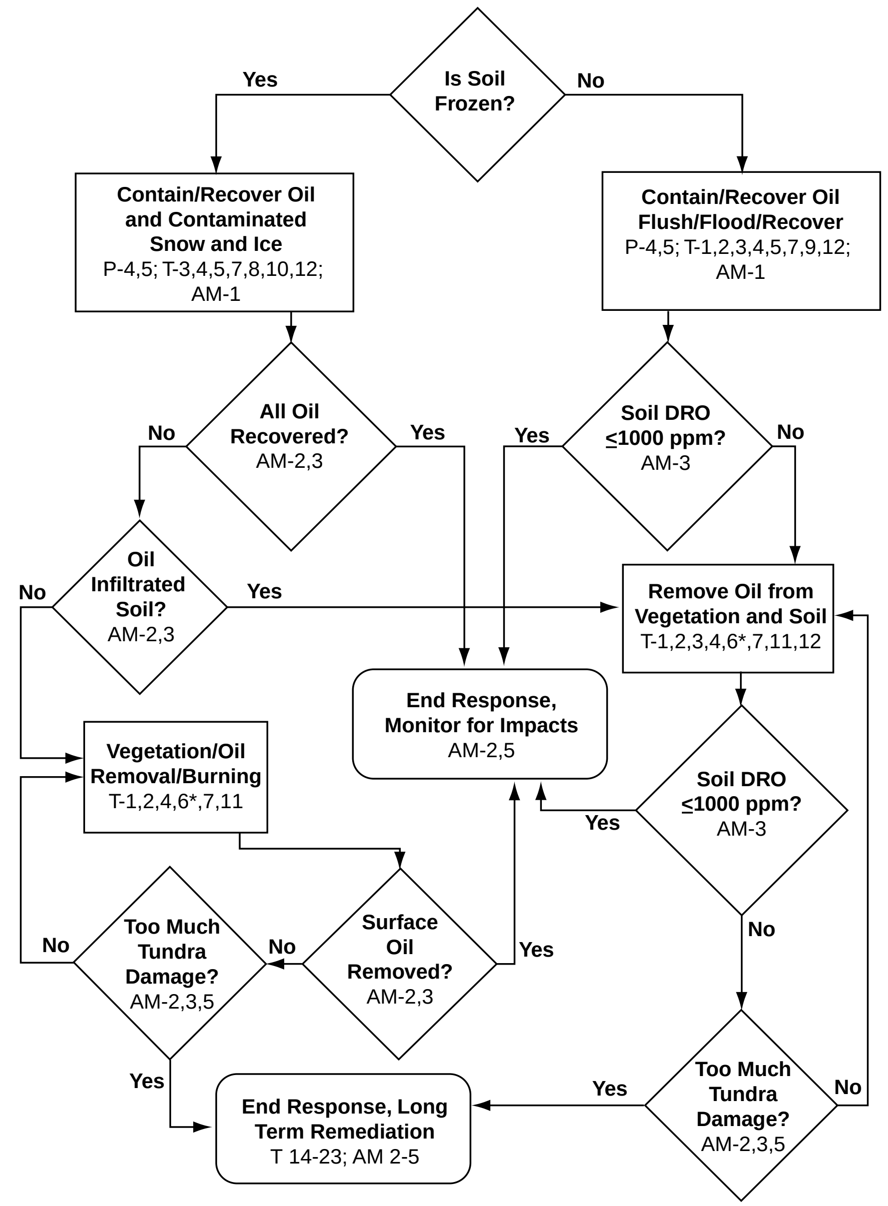
- ***Spill residual monitoring*** during treatment or long-term recovery can be based on sampling and laboratory analysis of soil (Tactic AM-3), field indicators (Tactic AM-2), and apparent phytotoxicity (revegetation test plots [Tactic AM-5]).
- ***Vegetation monitoring*** can be based on the amount of plant cover (percentage of area that plants occupy in a plot of land), the composition of the vegetation, and the condition (Tactic AM-5).
- ***Thermal effects (physical damage) monitoring*** can be based on simple visual observations and documentation of the site topography using ground or aerial photographs.

SAMPLE TUNDRA TREATMENT STRATEGIES

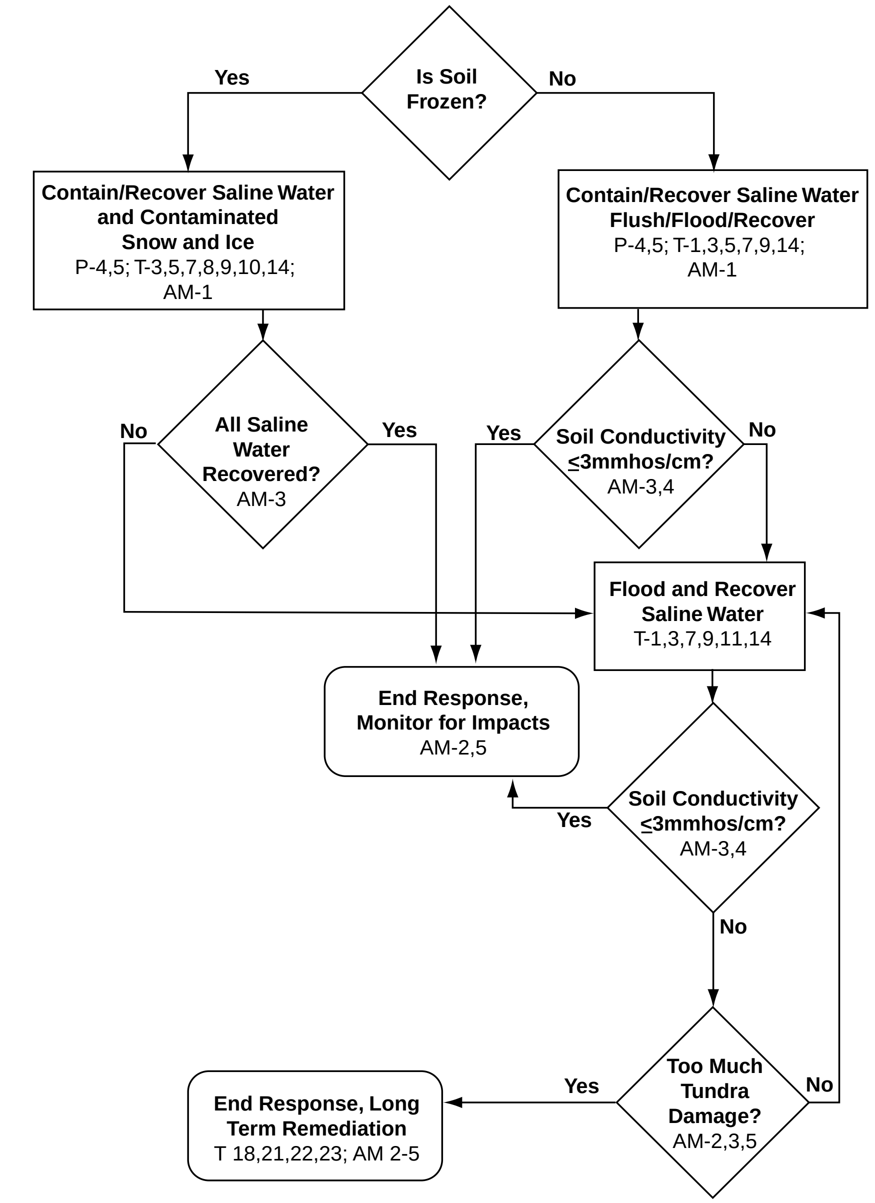
CRUDE OIL SPILL RESPONSE DECISION TREE



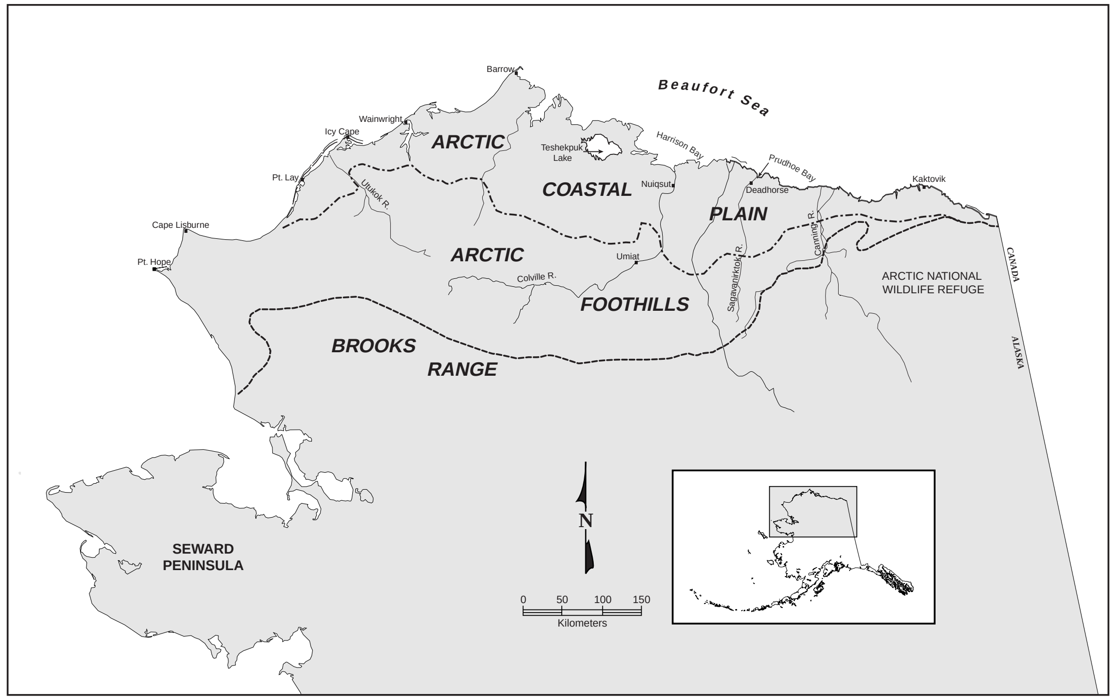
DIESEL SPILL RESPONSE DECISION TREE



SALINE WATER SPILL RESPONSE DECISION TREE



*** Permission from ADEC Spill Project Manager must be granted prior to burning.**



An understanding of the tundra environment is critical when choosing tactics and strategies for treating a spill. Following is a general overview of major tundra types and their characteristics. Although this discussion focuses on Alaska's North Slope tundra, the planning, treatment, and monitoring tactics in this manual apply to tundra environments elsewhere in Alaska.

WHAT IS TUNDRA?

"Tundra" is a word used to describe the treeless landscape found north of the boreal forest and above tree line in the mountains throughout Alaska (Lincoln, 1987). Tundra occurs where extreme winter cold and wind, brief cool summers, and shallow continuous permafrost prevent trees from growing. Seasonal thawing of the surface layer of permafrost in arctic tundra creates an "active layer" of thaw a few inches to a few feet deep each summer. The rooting depth of plants and the infiltration of water are limited to this active layer. Tundra vegetation is characterized by low-growing plants including mosses, lichens, grasses, sedges, and dwarf shrubs. The extreme conditions found in tundra environments limit the variety of plants that can survive.

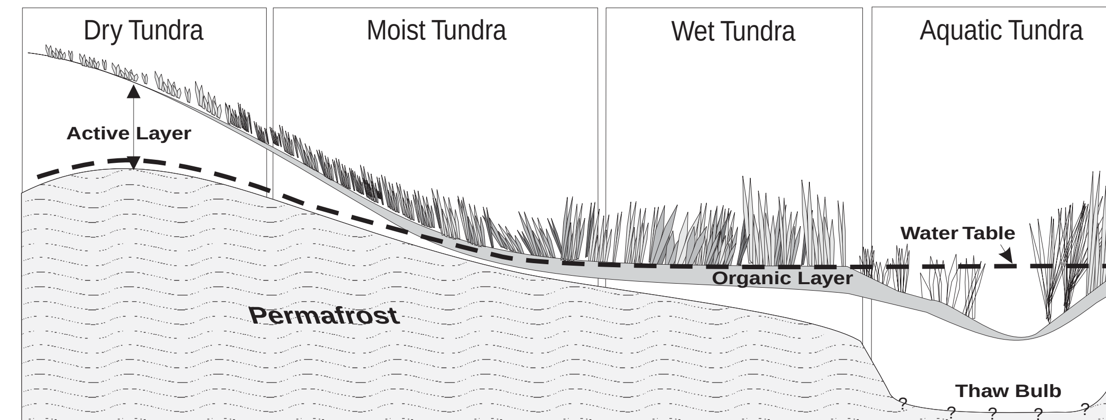
WHAT ARE THE TYPES OF TUNDRA?

The major tundra types recognized in Alaska are (Walker, 1983): ponds (aquatic tundra), marshes (wet tundra), bogs (moist tundra), and drier upland areas (dry tundra). These tundra types occur in three major geographic provinces on the North Slope of Alaska: 1) the coastal plain, 2) the foothills, and 3) the mountains of the Brooks Range, as well as on the Seward Peninsula.

The coastal plain generally supports wet tundra due to the subtle topographic relief and the shallow, saturated active layer. Here, "patterned" or "polygonal" ground results from ice wedges or frost action. The foothills generally support moist tundra on the slopes, wet tundra in low areas, and dry tundra on the exposed hilltops and ridges. Polygonal ground is less common here. In the Brooks Range and in other mountain ranges in Alaska above the treeline, dry tundra predominates. High shrub thickets develop in floodplains in less exposed areas or where snow accumulates and protects plants from harsh winter winds. In the braided channels of the active floodplains, the soil surface is frequently barren.

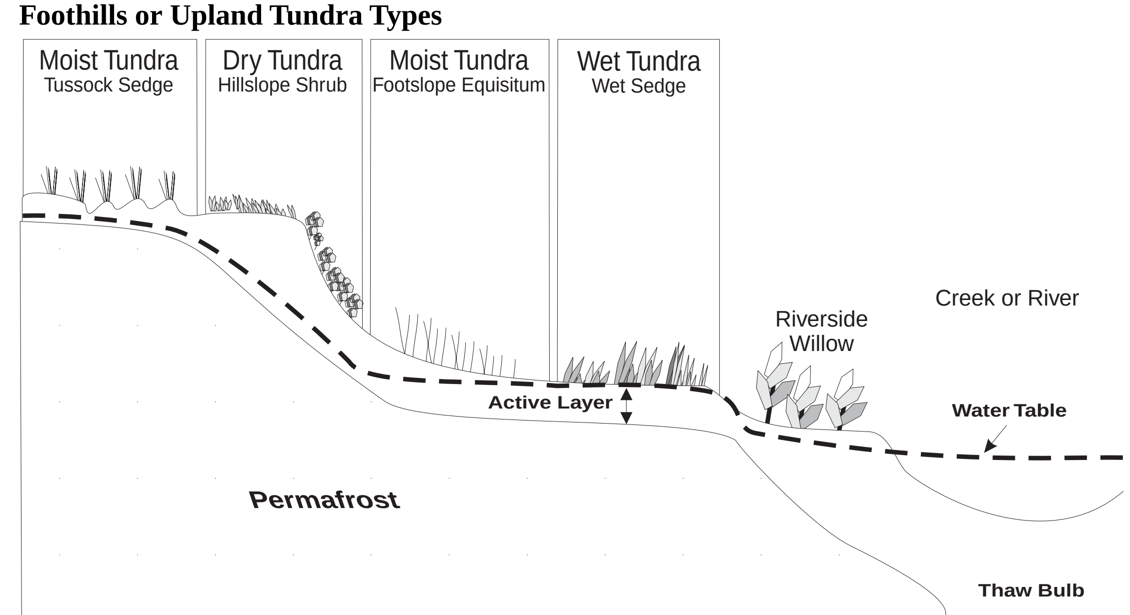
The following drawings illustrate topographic features and subsurface conditions associated with the general types of tundra on the coastal plain (Walker et al., 1980) and in the foothills (Walker et al., 1989) of the North Slope. The example plant communities listed for the coastal plain are just a few of the common types among more than 30 community types that occur there.

Coastal Plain or Lowland Tundra Types



Dwarf Shrub, Crustose-Lichen Tundra Lichens Mountain-Avens (*Dryas*)	**Moist Sedge, Dwarf Shrub Tundra** Cotton grass (*Eriophorum*) Sedge (*Carex*) Mountain-Avens (*Dryas*) Grasses (*Poa, Arctogrostis*) **Moist Tussock Sedge, Dwarf Shrub Tundra** Cotton grass (*Eriophorum*) Mountain-Avens (*Dryas*) Willow (*Salix*) **Moist Low Shrub Tundra** Dwarf Birch (*Betula*) Willow (*Salix*) Blueberry/Cranberry (*Vaccinium*) Labrador-Tea (*Ledum*)	**Wet Sedge Tundra** Water sedge (*Carex aquatilis*) Arctic pendant grass (*Arctophila fulva*) Other sedges (*Carex*) Cotton grass (*Eriophorum*) Fisher's tundra grass (*Dupontia fisheri*) **Wet Saline Graminoid Tundra** Creeping alkali grass (*Puccinellia phyragodes*) Happner's sedge (*Carex subspathacea*) Scurvy-grass (*Cochlearia*)	**Aquatic Tundra** Water sedge *(Carex aquatilis)* Arctic pendant grass *(Arctophila fulva)* Mare's tail *(Hippuris)* Marsh-marigold *(Caltha)* Marsh cinquefoil *(Potentilla palustris)* Buckbean *(Menyanthes)*

Foothills or Upland Tundra Types



Aquatic Tundra

- <u>Occurrence</u>: Open water areas of ponds, lakes and streams. May occur as an extension of adjacent wet sedge tundra into ponds or lakes.
- <u>Common Plants</u>: Arctic pendant grass (*Arctophila fulva*), water sedge (*Carex aquatilis)*, mare's tail (*Hippuris* spp.), marsh-marigold (*Caltha* spp.), marsh cinquefoil (*Potentilla palustris*) and buckbean (*Menyanthes* spp.).
- <u>Soils</u>: Thick layer of aquatic sediments made up of organic matter and peat.
- <u>Permafrost</u>: Deep at maximum thaw. Usually a "thaw bulb" below ponds, lakes, and streams caused by the water collecting heat from solar radiation.

Wet Tundra

- <u>Occurrence</u>: Where standing water persists through the growing season at depths less than 1 foot. Frequently along the margins of ponds, lakes and streams, in the low centers of polygon troughs, and within the wet areas of drained lake basins. This is the most common tundra type on the coastal plain. These are low-lying areas that accumulate melt water from adjacent higher ground due to the poor drainage.
- <u>Common Plants</u>: Aquatic emergent plants including arctic pendant grass (*Arctophila fulva*) or water sedge (*Carex aquatilis)* growing in standing water at the edge of ponds. Where the soil is saturated but without standing water, sedges and other grass-like plants thrive. Together these and many other wetland plants occur in a mosaic of open water, aquatic emergent vegetation, and stands of sedges.
- <u>Soils</u>: A layer of organic matter and roots forms a mat up to about 1 foot thick. The organic soil layer and root zone are thicker in wet tundra compared to dry or moist tundra. Ponds and standing water are typical at wet tundra sites, and soil pore spaces are saturated with water during the growing season.
- <u>Permafrost</u>: Moderate to deep at maximum thaw. The high thermal conductivity of the water can melt the upper layer of permafrost in the summer despite the insulating effects of the highly organic root mat. This *active layer* may extend to about 3 feet below the tundra surface in wet tundra.

Moist tundra

- <u>Occurrence</u>: Usually where the soil is saturated throughout the growing season and standing water is shallow or present for only a part of the growing season. Areas of moist tundra on the North Slope include the slopes of hills and the rims of polygons.
- <u>Common Plants</u>: Sedges (*Carex* spp.), cotton grass (*Eriophorum* spp.), dwarf shrubs like willow (*Salix* spp.), birch (*Betula* spp.) and mountain-avens (*Dryas* spp.), grasses, and broad-leaved herbaceous plants. A common type of moist tundra found in the foothills of the North Slope is tussock sedge tundra dominated by cotton grass (*Eriophorum vaginatum*), dwarf shrubs and *Sphagnum* moss.
- <u>Soils</u>: A dense, compressed root mat overlays silt or clay loam mineral soils.
- <u>Permafrost</u>: Active layer thinner than in wet or dry tundra due to the dense insulating organic mat and intermediate soil wetness.

Dry Tundra

- <u>Occurrence</u>: Where good drainage and a deep active layer create relatively dry soil conditions throughout the growing season. Throughout the slopes of mountain ranges, on ridges and hilltops in foothills, and on upland areas, stabilized dunes, pingos, and other well-drained locations on the coastal plain.
- <u>Common Plants</u>: Dwarf shrubs like birch, willow, blueberry and cranberry (*Vaccinium* spp.) and mountain-avens, evergreen shrubs like Labrador-tea (*Ledum* spp.), crowberry (*Empetrum* spp.), arctic bell-heather (*Cassiope* spp.), and manzanita (*Arctostaphylos* spp.) along with lichens, mosses, and grasses.
- <u>Soils</u>: Dry tundra soils have a thin root mat and low organic matter content compared to moist and wet tundra. Ample drainage reduces the ability of the thin root mat to hold moisture.
- <u>Permafrost</u>: The thaw depth usually is greater than 3 feet in dry tundra.

Why is Tundra So Sensitive to Disturbance?

Tundra environments are especially sensitive to disturbance for several reasons:

- Continuous permafrost
- Short growing season
- Extreme winter wind and cold temperatures

The tundra vegetation layer and root mat insulate the permafrost layer from the sun and warm surface air during the growing season. Surface disturbances can cause ice in the soil to melt, reducing the soil volume and causing subsidence (thermokarst). Drainage patterns are affected by subsidence, leading to further changes in topography and hydrology. Thermokarsting of dry or moist tundra could lead to formation of wet or aquatic tundra.

Tundra soils develop slowly in the Arctic, because the cold climate and short growing season limit the rate of plant matter decay by inhibiting chemical reactions and biotic activity. Water plays a major role in maintaining tundra vegetation on the North Slope. The combined water loss from evaporation and transpiration (water loss from plants) exceeds the precipitation received during the summer growing season. During June and July the water levels drop and then increase with precipitation in August, along with reduced evaporation and transpiration (lower temperatures and reduced plant growth). Wet and moist tundra, as well as ponds, capture and then lose the annual snowmelt runoff in the brief arctic summer. Annual evaporation and transpiration from wet and moist tundra exceed annual precipitation, and as a result, snowmelt runoff from surrounding upland areas is necessary to maintain wet conditions. Surface flow is usually observed only during and immediately following snowmelt. Subsurface water flow rates are generally low due to mostly impervious soil and low topographic gradients.

Why Are Spills on Tundra Difficult to Treat?

Treatment of spills to tundra is difficult for several reasons:

- Short summer season available when most treatments can be implemented
- Cold temperatures that limit biological activity and biodegradation
- Physical damage that may be caused by surface activities
- Remote locations and high mobilization effort
- Treatment is more complicated where patterned ground or tussocks occur

Acid or Alkaline Tundra?

The alkaline soil conditions of the coastal plain around the Prudhoe Bay oil field and along the Dalton Highway are unique for arctic tundra (Walker and Everett, 1991). Windblown dust from the Sagavanirktok River has deposited minerals that make the soil alkaline (pH>7), thus influencing soil and plant community development. Tundra treatment measures may vary depending on whether the soils are acidic (pH<7) or basic (pH>7). Arctic tundra is commonly acidic due to accumulation of peat and humic acids produced by peat.

The alkaline soil properties affect the types of plants able to grow in the affected areas. For example, shrubs like blueberry and cranberry (*Vaccinium* spp.), birch (*Betula* spp.), and some species of willows (*Salix* spp.) are less abundant in alkaline soil areas, whereas other plants such as mountain-avens (*Dryas integrifolia*) are more common in alkaline tundra than acidic tundra.

This tactic provides a brief description of some potential spill substances and their expected effects on tundra vegetation and soils. Data are limited, and much of what is known about the effects of spills to tundra is the result of spills or field experiments in this region. The companion manual to this publication, “Tundra Spill Cleanup and Remediation Tactics: A Study of Historic Spills and Literature” (Behr-Andres, 2001), provides the scientific basis for decisions on tactics to be used for a particular spill scenario.

This discussion focuses on hazardous substances that are produced, extracted, or used in the production or extraction of oil and gas in Alaska’s arctic oilfields. Hazardous substances of concern include crude oil, diesel fuel, gasoline, Therminol, glycol (ethylene and propylene), methanol, drilling fluids, produced water, and seawater. In tundra communities, diesel, gasoline, and sewage spills to tundra are the primary potential concerns. Other substances, such as hazardous wastes, may be spilled on tundra but would usually be spilled in small quantities and could require development of spill-specific treatment regimes.

It should be noted that in a typical spill in oil-producing areas, more than one substance may be released. A typical example would be a release of saline water and crude oil.

CRUDE OIL

Crude oil is a substance of fossil, biogenic origin, which contains thousands of organic and a few inorganic compounds. Included in crude oil are natural gas, liquefied petroleum oils, resins, and asphaltenes. Hydrocarbons, which are composed only of carbon and hydrogen atoms, are the most abundant components of crude oil. Other components include sulfur, oxygen, nitrogen, and a variety of metals which are bound to organic compounds or exist as inorganic salts.

The composition of crude oil determines its behavior and fate when spilled onto the tundra. It also affects the responses of tundra vegetation to oiling. Crude oil can kill plants in several ways. The light fractions of the crude oil, consisting of short-chain and aromatic hydrocarbons, cause the most severe damage to plants by penetrating and destroying the plant tissues. If the affected plant tissues are necessary to the plant’s survival, the plant could be killed. Otherwise, the plant may survive with reduced biomass and vigor. Heavier fractions of crude oil can coat the surface of the leaves and prevent gas exchange, which is necessary for normal plant function. The plant may be killed if enough leaf or stem tissue is oiled.

Crude oil can also damage vegetation indirectly by creating hydrophobic (unwettable) soil conditions (Walker et al., 1978; McKendrick, 1999). Plants, particularly those in moist and **wet tundra**, require substantial amounts of soil moisture and are unable to survive such conditions. Crude oil can also displace the air occupying pore spaces in **dry or moist tundra** and cause the soil to become anaerobic. Moreover, the added organic carbon in the form of crude oil can stimulate microorganisms to decompose the oil, which can deprive higher plants of nutrients (McKendrick, 1999).

Several factors influence the toxic and physical effects of crude oil on tundra vegetation, including season that the spill occurs, weathering, and soil properties. For example, if the oil is perched on top of frozen or water-saturated soils, the most toxic aromatic fractions will evaporate and may not penetrate the soil (McKendrick, 1999). This is especially important for sedges and grasses — common plants in tundra — because the perennating buds lie below ground and can escape the most damaging components of crude oil when the oil does not penetrate the surface because the ground is frozen or water-saturated (Everett, 1978). Bark provides some protection for stems of shrubs, and their perennating buds are elevated above the soil surface, allowing them to escape damage if the oil has spread in a thin layer across the soil surface. **Dry tundra habitats are thought to be more susceptible to crude oil damage because the aromatic fractions can be carried into the soil before they evaporate, becoming trapped where roots and perennating buds can be killed (McKendrick, 1999).** Crude oil does not appear to be toxic to tundra vegetation at total petroleum hydrocarbon (TPH) levels of less than 13,000 mg/kg (Burgess et al., 1995, Cater and Jorgenson, 1999).

Despite the acute short-term adverse effects of crude oil on tundra vegetation, notable recovery has been documented in long-term observations of oiled sites (McKendrick, 1999). In an experiment on North Slope, wet tundra coated with crude oil at a rate of 250 barrels per acre (corresponding to a thickness of about 10 mm or about 3/8 inch) showed nearly complete natural revegetation with native species after 24 years without cleanup or treatment. However, crude oil applications of 1,000 barrels per acre (thickness 40 mm or about 1.5 inches) to wet tundra inhibited revegetation substantially. Even after 24 years, these areas had less vegetation cover and fewer species than nearby unoiled areas (McKendrick, 1999). In general, vascular plant cover observe 24 years after experimental oiling decreased with increasing experimental oil-application rates. These results correspond well with findings by Cater and Jorgenson (1999), who compared relationships between soil hydrocarbon concentrations and vegetation cover among several accidental crude-oil spill sites on wet tundra on the North Slope. The following conversion table presents oiling rates (volume units/area units) in terms of petroleum hydrocarbon concentrations (part per million (ppm) or milligrams per kilogram (mg/kg) in soil.

Conversion Table for Oiling Rates, Surface Thickness, and Soil Concentrations of Crude

SURFACE OILING RATE				SURFACE THICKNESS		PERCENT OIL IN SOIL BY VOLUME		PERCENT BY DRY WEIGHT (soil bulk density = 0.4)		PARTS PER MILLION (ppm; mg/kg) DW	
liters/ m^2	quarts /yd^2	gallons /acre	bbl /acre	mm	inches	Soil Oiling Depth (cm) 10	5	Soil Oiling Depth (cm) 10	5	Soil Oiling Depth (cm) 10	5
10	2 1/4	10691	255	10	3/8	10	20	22	44	220000	440000
5	1	5346	127	5	3/16	5	10	11	22	110000	220000
1	1/4	1069	25	1	1/16	1	2	2.2	4.4	22000	44000
0.1	-	107	3	0.1	-	0.1	0.2	0.22	0.44	2200	4400

In general, shrubs, mosses and forbs have been shown to be more sensitive to crude oil than have grasses and sedges (Walker et al., 1978; Jorgenson and Cater, 1992). However, trampling and heavy equipment use for spill response can also cause considerable damage to the tundra. The possible damage done by responding needs to be weighed against the benefits of additional crude oil removal.

The initial spill response strategy for crude oil spills to tundra should be to prevent further spread of the oil, to prevent wildlife injury and to recover as much free product as possible. Rapid spill response is necessary to prevent the penetration of crude oil into the tundra soil which may result in the injury of plant roots and perennating buds. Water-saturated soils help to minimize soil penetration of petroleum into wet tundra, but moist and dry tundra are much more susceptible to soil penetration due to less soil moisture and greater soil pore space.

It is possible to recover more of the crude oil without injury in tundra when the spill occurs when soils are frozen and snow is present. Frozen soils help to prevent soil penetration and snow can act as an adsorbent, limiting lateral spread. Further advantages for winter spill response are that use of heavy equipment and foot traffic are less damaging to tundra, plants are dormant and wildlife is less prevalent. Winter spill response to crude oil spills may include vacuuming, scraping up crude-saturated snow and ice, flooding and skimming. While winter crude oil spills may be effectively cleaned up with little soil penetration, responses to crude oil spills in summer are more difficult. Summer spill response is problematic because of greater wildlife presence, increased difficulty in accessing the site and performing work without trampling the tundra, and lack of a frozen layer to prevent vertical migration. Summer spill response tactics for crude oil spills usually include vacuuming and skimming free product and using flooding and flushing to lift crude oil from the tundra soil and plants.

Burning can be a useful tool to remove residual crude oil from the soil surface or from vegetation following the use of other tactics to remove the majority of crude oil. **Permission from the ADEC project manager for the spill must be granted prior to burning.** Burning is not a good option for dry tundra because of the likelihood of burning soil organic matter and because perennating buds of many species in dry tundra occur above ground where they are susceptible to fire damage.

DIESEL FUEL

Diesel, which is a petroleum product refined from crude oil, is composed of many different chemicals. When the fuel is spilled on tundra, the volatile diesel components (aromatic hydrocarbons such as benzene) evaporate, changing the chemical composition of the spill. Other chemicals in the fuel will dissolve into active-layer water or surface water, while some chemicals such as polynuclear aromatic hydrocarbons (PAHs) may adsorb to fine particles in tundra soil and persist for a long time. Soil microbes that degrade the hydrocarbons may be unable to metabolize the adsorbed PAH molecules, and biodegradation is inhibited. However, the soil adsorption of PAH molecules can reduce phytotoxicity, since adsorbed chemicals are not available for plant uptake.

Diesel spills to tundra are generally more damaging to soil and vegetation than spills of crude oil (Walker et al., 1978; Jorgenson and Cater, 1996). Diesel range organics (DRO) levels of 1,000 - 2,000 mg/kg were found to inhibit seed germination and plant growth (Cater et al., 1997). DRO levels of 1,600 and 2,800 mg/kg were found where vegetation was stressed or dead where diesel was spilled at Wainwright, Alaska (Woodward-Clyde, 1995a, 1995b). Lawson et al. (1978) examined several sites on the National Petroleum Reserve 28 years after a diesel spill and found that little vegetation recovery had occurred.

Direct exposure of plant leaves to diesel will kill the leaves and can kill the entire plant if roots and perennating buds are also exposed. Diesel spills to dry or moist tundra are potentially more damaging to tundra vegetation than is a similar spill to wet tundra. The water-saturated root zone of wet tundra may confer initial soil protection, though the presence of water-soluble hydrocarbons like napthalene in diesel results in eventual penetration of these toxic fractions into the soil and subsequent plant injury.

Rapid response to diesel spills is critical to minimizing surface and vertical migration in tundra. Containment and product recovery must be completed as soon as possible after the spill. In winter, snow and ice help to contain diesel spills and minimize soil penetration with the result that many winter spills have been cleaned up with no damage to tundra. However, a review of summer diesel spills (AMEC, 2001) showed that summer diesel spills to tundra always produced vegetation injury. Flooding and flushing, raking, and cutting of diesel-coated vegetation may be used to remove residual diesel contamination. Prior to burning, permission must be granted by the ADEC project manager handling the spill. Soil aeration, water management, fertilization and revegetation are useful long-term remediation tactics for diesel spills.

GASOLINE

Gasoline is highly volatile and flammable refined petroleum product that spreads rapidly to a thin sheen on water or wet soil. Evaporation rates are very high; gasoline contains a larger percentage of volatile aromatic compounds than either diesel or crude oil.

Gasoline spills on tundra are generally more damaging to soil and vegetation than spills of crude oil. Direct contact of plant leaves with gasoline will often kill the entire plant. Some **wet tundra** vegetation may be initially resistant to gasoline spills where interstitial water protects the root zone; however, like diesel, gasoline has water-soluble fractions which may migrate into the root mat and organic soils in a relatively short time. **Moist and dry tundra** are highly susceptible to the effects of gasoline spills for the same reasons they are susceptible to the effects of diesel spills—rapid penetration of the soil and trapping of the toxic aromatic fractions in the root zone, where they can be toxic to vegetation. Depending on incident-specific and site-specific conditions, overall phytotoxic effects of diesel may be higher than those of gasoline. Many of the harmful aromatic fractions of gasoline may evaporate before penetrating tundra soils.

SALINE WATERS AND SUBSTANCES

Seawater and brine are used on the North Slope as part of enhanced oil recovery processes and are transported via pipeline and truck. Produced water is generally separated from the oil stream and reinjected at well heads. Fire-fighting chemicals also contain salts and cause similar effects to tundra vegetation.

High levels of sodium and chloride ions in saline spills increase the osmotic potential of soil water, making water uptake more difficult or impossible for non-salt-tolerant tundra plants. Depending on spill concentrations, salt-impacted vegetation may wilt, become discolored, drop leaves, or die within hours or days of contact with foliage or roots (Barker, 1985). Saline substances spread rapidly on **wet and moist tundra**, and newly affected areas may become apparent with each growing season as the spill spreads (Barker, 1985; Reiley et al., 1995). Jorgenson et al. (1987) found that damage to tundra vegetation was moderate at soil salinity levels of 2-3 mmhos/cm and severe at 6-10 mmhos/cm. Simmons et al. (1983) made controlled releases of seawater to tundra at 8 sites in the Prudhoe Bay, Alaska area. They found that live plant cover was reduced by 61 to 87% in dry and moist tundra sites.

Crude oil is often a part of saline water spills, and the emphasis on cleanup has been directed more at cleaning up the crude than the saline water. However, the salts affect vegetation at much lower levels, and the effects are usually longer lasting since salts do not bioattenuate. Thus more of the emphasis on cleanup of mixed saline water and crude spills should be placed on cleanup of the saline water.

Initial spill response for spills of saline substances should include containment and removal of salt water. Repeated flooding and water recovery has been found to be an effective tactic for removing residual salts. Long-term remediation tactics that may have potential are addition of gypsum (Cater and Jorgenson, 1995) and planting of salt-tolerant plant species.

DRILLING MUDS AND FLUIDS

Drilling muds and fluids consist of a complex and variable mixture to meet oil-well drilling needs and usually contain bentonite clay, saline substances and heavy metals. Tundra vegetation and aquatic invertebrate communities in Alaska and Canada have been damaged by drilling muds leaking from reserve pits that are used to store drilling muds. Spills of drilling fluids to tundra have also resulted from well blowouts. Drilling mud spills are usually accompanied by varying amounts of crude oil and saline water.

The salinity of drilling muds and smothering due to burial appear to be the primary factors associated with toxicity of drilling muds to tundra plants (McKendrick, 1986; Railton, 1975; Jorgenson and Kidd, 1994; Burgess et al., 1997). Railton (1975) found that plant recolonization decreased with increasing thickness of drilling mud deposits. Little plant growth occurred on drilling mud deposits six inches deep. Tussock grass (*Eriophorum vaginatum*) and woody plants survive these spills better than other plants because they are not totally buried. The salinity effects of drilling muds appear to be caused by high levels of sodium whereas salinity effects of produced water or seawater are caused more by high chloride levels (Burgess et al., 1997).

For spills that occur during winter, careful removal of frozen drilling muds to within 1 to 2 inches of the soil surface followed by vacuuming appears to be an effective cleanup tactic. Flushing and subsequent water removal may also be warranted.

SYNTHETIC FLUIDS

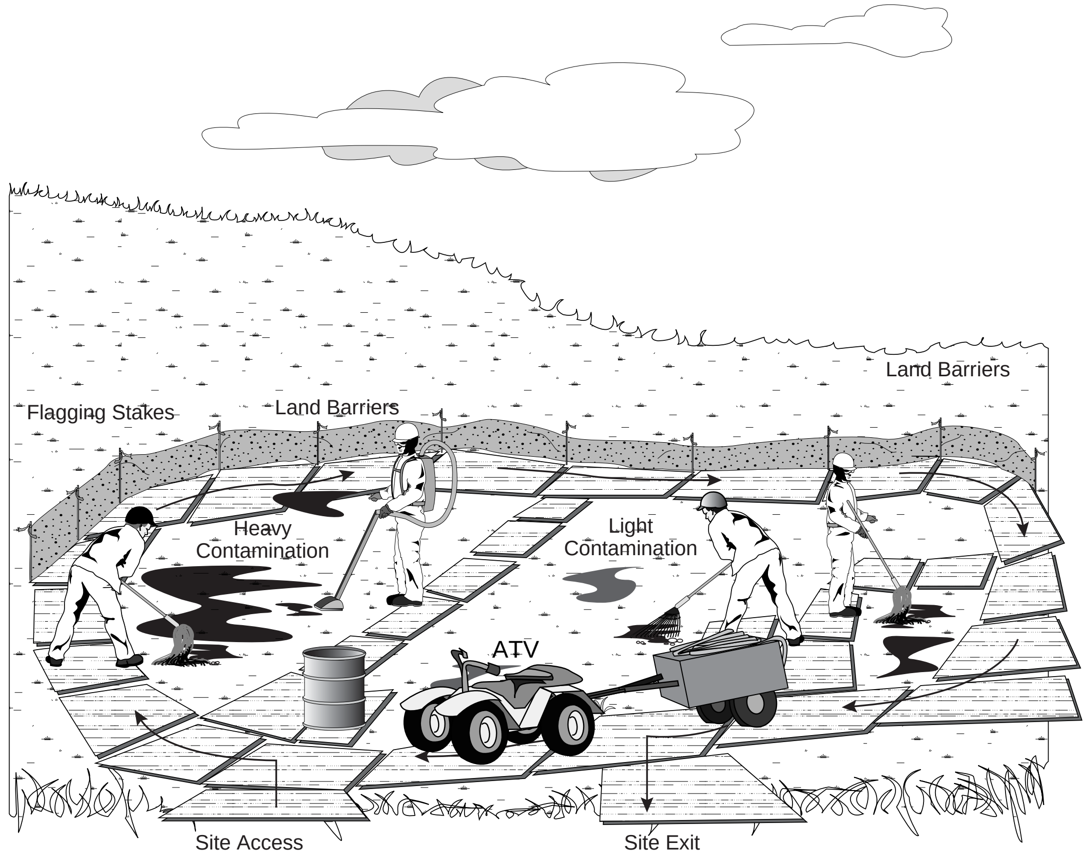
Methanol. Also known as wood alcohol or methyl alcohol, methanol is a highly flammable, volatile solvent used in oil field operations. Methanol is a clear, colorless liquid with a pungent odor, is completely soluble in water, and is expected to degrade quickly in both soil and water (estimated half-life is between 1 to 10 days [J.T. Baker MSDS]). Methanol evaporates quickly from soil and water when exposed to air. This chemical is highly toxic to wildlife, but its toxicity to plants is not well known. Following a winter spill on the Alaska North Slope, methanol levels in soil of 4,300 mg/kg were measured after initial cleanup. Little damage to tundra was found the following spring, but the methanol may have been diluted by spring snow melt and evaporation (Cater et al., 1998). The toxic effects of methanol may be reduced by dilution with water or by evaporation.

Initial spill response for methanol spills should focus on wildlife protection and then containment and recovery.

Glycols. Ethylene and propylene glycol are synthetic liquids that absorb water. They are used as antifreeze for vehicles, and are used in heating systems and in industrial applications. Glycols are clear, odorless liquids that are miscible with water and have low vapor pressures. When released into the environment, glycols have short half-lives (3 to 10 days at warm temperatures) and may be biodegraded by microorganisms (Howard, 1991). Abiotic transformations in soil or water are not significant except that glycols are subject to photo-oxidation. There is no information on the toxicity of glycols to plants. Ethylene glycol is highly toxic to animals, so initial response to spills of this compound should focus on wildlife protection, followed by containment and recovery.

Standard containment and product recovery tactics followed by flooding and water/glycol recovery are standards for glycol spill response on tundra.

Therminol. An insoluble organic liquid, therminol (Therminol 59) is commonly used as a heat transfer fluid for pump stations and well houses. In its raw form, it is a clear yellow liquid exhibiting a mild hydrocarbon odor and is viscous even in below-freezing temperatures. Little is known about the environmental toxicity of therminol. Biodegradation tests suggest that it is resistant to biodegradation (Solutia MSDS). No long-term studies have been made regarding the effects of therminol spills in tundra. Because the toxicity of therminol is not known, high removal rates should be adhered to following a spill. Standard containment and product recovery techniques followed by flooding and further product removal are recommended tactics.



Physical damage to the tundra can be an unwelcome consequence of treatment. Tundra may be physically damaged by:

- Trampling or repeatedly walking over the same area,
- Driving vehicles or heavy equipment on the tundra when the active layer is thawed, and making repeated trips with heavy equipment when tundra is frozen,
- Excavating (Tactic T-13) or trenching (Tactic T-9),
- Using high-pressure or hot water for flushing (Tactic T-2) or flooding (Tactic T-1), or
- Injuring the root mat while burning (Tactic T-6) or scraping (Tactic T-8), especially when the soil is very dry.

Activities that require vehicles or repeated trips on foot over thawed tundra destroy vegetation and permanently compress organic soils. These ruts or compressed areas may change site drainage patterns, causing drying of some areas and inundation of others. Damage to vegetation and compression or removal of organic soils and may result in loss of insulating effects of the tundra surface, which could cause underlying permafrost to thaw and the soil to subside ("thermokarst"). Thermokarst can change dry or moist tundra to wet or aquatic tundra by creating depressions that fill with water and change habitat conditions. Once the thermal regime and drainage of an area are disturbed, the site may remain in the altered state for many years.

Some options for minimizing physical damage to tundra are:

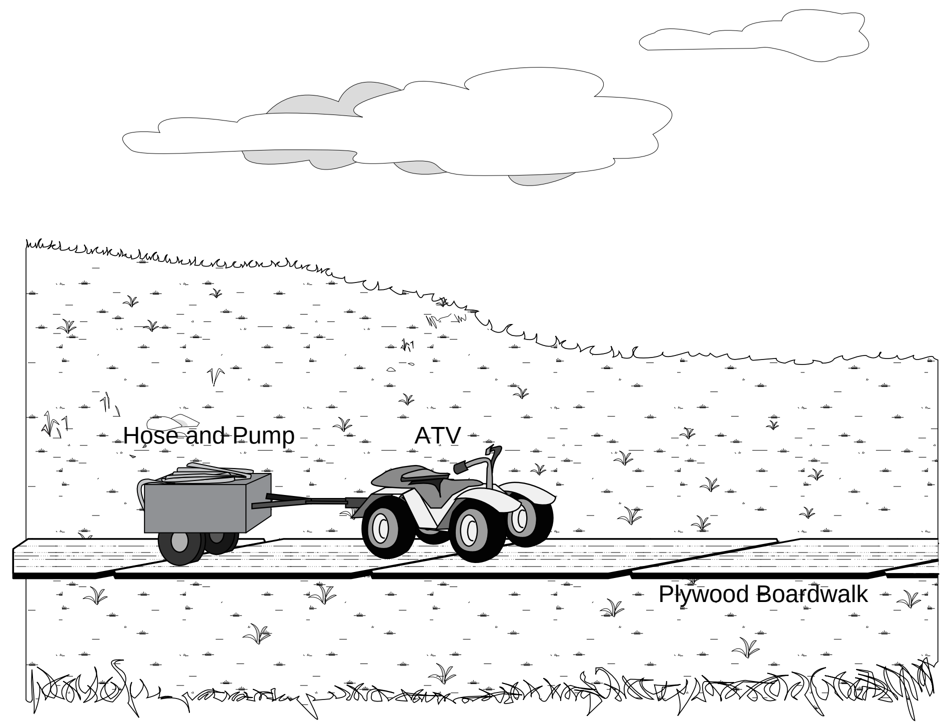
- Limiting travel on tundra as much as possible
- Limiting use of invasive treatment tactics as much as possible
- Using plywood as boardwalks or working platforms for light equipment
- Using snowshoes for repeated trips on foot over the tundra
- Using existing roads as much as possible
- Using existing gravel pads for staging where possible
- Restoring natural contours and drainage by filling excavations
- Replacing removed organic layer with peat or sod
- Tilling highly compressed areas (Tactic T-19) and enhancing revegetation

APPLICABILITY

	APPLICABILITY	COMMENTS
SPILLED SUBSTANCE	All	
TUNDRA TYPE	All	• Generally, wet sites are more easily disturbed by traffic but recover faster than dry sites. Dry sites are less susceptible to damage from traffic than wet sites but recover more slowly.
SEASON	All	• All tundra types are more susceptible to physical damage while the active layer is thawed.

CONSIDERATIONS AND LIMITATIONS

- All repetitive foot traffic should be limited to boardwalks whenever possible.
- Boardwalks should be light enough to be moved manually. Boardwalks can be moved as workers concentrate on different areas within the site.
- If treatment tactics require heavy equipment, tundra travel permits and proper road construction may be required (Tactic P-5).



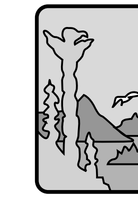
Tundra travel permits are required for vehicles traveling off-road in many tundra areas. In many cases, industry operators have tundra travel permits in place. If no permits are in place, contact the appropriate landowners and agencies, who may require anywhere from one day to 2 months to issue permits. The following agencies issue tundra travel permits:

- Alaska Department of Natural Resources, Division of Land (state-owned land)
- North Slope Borough (Borough-owned land)
- Alaska Coastal Management Program (if site is in the coastal zone)
- Alaska Department of Fish and Game (if site is near river or stream)

For state-owned land on the North Slope, the policy of the Alaska Department of Natural Resources, Division of Land requires a permit for any vehicle traveling on tundra during any season. Permits are issued for either summer tundra travel (July 15 until freeze-up), winter tundra travel (freeze-up until breakup), or both. No off-road travel except for true emergencies is permitted for the period from breakup until July 15.

WINTER TUNDRA TRAVEL

In Alaska, tundra is generally open to off-road travel when the ground is frozen to a depth of 12 inches and when there is approximately 6 inches of snow on the ground. The date of tundra opening on the North Slope has ranged from as early as November 4 to as late as January 1. Once the tundra has been opened in the winter, there are no restrictions on the type of vehicles that may operate on the tundra. In years of limited snowfall, the tundra may be opened conditionally, with the stipulation that vehicles are restricted to areas where snow has drifted such that enough snow is present to prevent damage to the tundra vegetation.



Alaska North Slope tundra is closed when it appears that thawing has resulted in snow that will be too soft or too limited to permit travel without damaging vegetation. Operators are then given a 72-hour notice to move vehicles and other equipment off the tundra.

SUMMER TUNDRA TRAVEL

The Division of Land has approved use of 4-wheel all-terrain vehicles on boardwalks placed on tundra (Tactic P-4) in the summer. A permit is required for this kind of travel. The Division of Land will permit use of heavy equipment on tundra during summer months for special uses (e.g., excavating contaminated soil) on a case-by-case basis.

The following vehicles have been tested and approved by the Division of Land for summer tundra travel:

- Argo 8 1/C with smooth tracks
- Roller-driven Rolligon
- Haggland Bearcat with smooth track configuration
- Tucker Snocat with smooth track configuration
- Airboats (for use in spill drills and exercises only)

The purpose of vehicle testing is to determine which vehicles can operate on the tundra during the summer without causing damage to the vegetation. Vehicles are approved in the configuration tested; for example, a vehicle tested with a payload of 1,000 pounds is limited to that payload when operating on the tundra. A vehicle tested and approved with smooth tracks would require retesting if the vehicle is to be operated with cleats or wheels.

The following stipulations apply to all summer tundra vehicles operating on state land:

- Operations are restricted to dry uplands whenever possible.
- Crossing wetlands shall be kept to an absolute minimum.
- Crossing ponds or lakes or the wetlands immediately bordering these areas is not authorized.
- Minimum-radius turns shall be avoided where possible.
- Multiple passes over the same area shall be kept to a minimum.
- All operators shall be made familiar with arctic vegetation types to ensure compliance with these stipulations.
- The state reserves the right to limit, restrict, or require retesting of vehicles at any time.